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JASA REVIEW-ARTICLE

# Navigating noisy waters: A review of field studies examining anthropogenic noise effects on wild fish[a]

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**ABSTRACT:**
Anthropogenic noise is globally increasing in aquatic ecosystems, and there is concern that it may have adverse consequences in many fish species, yet the effects of noise in field settings are not well understood. Concern over the applicability of laboratory-conducted bioacoustic experiments has led to a call for, and a recent increase in, field-based studies, but the results have been mixed, perhaps due to the wide variety of techniques used and species studied. Previous reviews have explored the behavioral, physiological, and/or anatomical costs of fish exposed to anthropogenic noise, but few, if any, have focused on the field techniques and sound sources themselves. This review, therefore, aims to summarize, quantify, and interpret field-based literature, highlight novel approaches, and provide recommendations for future research into the effects of noise on fish. © *2023 Acoustical Society of America.*
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## I. INTRODUCTION

In recent years, the effects of anthropogenic (man-made) noise on fishes have rightfully captured the attention of researchers and policy makers alike with concern over how it could impact imperiled fish populations (Gedamke *et al.*, 2016; Nolet, 2017; Popper *et al.*, 2014; Popper *et al.*, 2020; Hawkins *et al.*, 2020). However, current mitigation measures are largely precautionary, as not enough information is available for countries to provide specific criteria to which to adhere (Halvorsen *et al.*, 2017; Nolet, 2017; Hawkins and Popper, 2016; Hawkins *et al.*, 2020). While in extreme cases underwater noise can lead to injury or death of fish (McCauley *et al.*, 2003; Codarin *et al.*, 2009; Dahl *et al.*, 2020; Jenkins *et al.*, 2022), the more subtle effects are harder to define, so further investigation is necessary before mitigation protocols and regulations can be developed properly. For the purposes of the current review, we use the term "noise" to follow the definition in Cox *et al.* (2018) as sound that "conveys little to no intentional information."

Laboratory experiments have contributed to the majority of the current knowledge on the impacts of noise pollution on fish (e.g., Codarin *et al.*, 2009; Simpson *et al.*, 2015; Purser *et al.*, 2016); however, there is growing concern that laboratory findings do not capture the natural responses of wild fishes to underwater noise (Hawkins *et al.*, 2020; Jones *et al.*, 2019; Popper and Hawkins, 2018). Sound is misrepresented in a laboratory setting through its reverberations on the tank walls that unpredictably change the proportionality between sound pressure and particle motion, so the fish is not necessarily hearing ecologically relevant sounds (Parvulescu, 1967; Akamatsu *et al.*, 2002; Rogers *et al.*, 2016; Jones *et al.*, 2019).

Underwater sound exists as a pressure wave and as particle motion, but fish ears only respond to the particle motion component of the sound wave (Dijkgraaf, 1960; Putland *et al.*, 2019; Popper and Hawkins, 2018, 2021). There are fish that developed ancillary structures (e.g., swim bladders and other gas-filled vacuoles) that can transduce the pressure information into direct particle motion and, therefore, expand fish hearing abilities (Popper and Hawkins, 2018; Putland *et al.*, 2019). The relationship between particle motion and pressure can be difficult to quantify in shallow (<100 m) field settings and even more difficult in laboratory tanks, so care must be taken when interpreting acoustic studies conducted in enclosed laboratory tanks (Nedelec *et al.*, 2016a; Nedelec *et al.*, 2021).

Fishes held in captivity are also confined within the tanks, so natural escape responses to anthropogenic noise cannot be observed, and fish may experience elevated baseline stress levels, which can conceal the magnitude of observed effects (Purser *et al.*, 2016; Popper and Hawkins 2018). Additionally, captive-reared fish can show differences in gene expression relative to their wild counterparts through differing selective pressures (Jerem and Mathews, 2021), further altering their ability to represent the reactions of wild fishes. Thus, there is a growing need for the continued use of field-based experiments to meet the demand for real-world knowledge of the effects of anthropogenic noise in aquatic environments.

Sound can travel much faster underwater than through air and disseminates information in all directions of the source, making sound an incredibly important sensory modality and form of communication for fishes (Rogers and Cox, 1988).

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Noise created by human activity in aquatic ecosystems can be produced by recreational and commercial boats and vessels, resource-focused ocean exploration, (i.e., seismic testing), aquaculture, or construction (i.e., pile driving) (Slabbekoorn *et al.*, 2010; Hawkins *et al.*, 2020). The addition of these sounds can interfere with ecologically important sounds for fish (i.e., used for habitat selection, migration, mating, or territory defense) (Hawkins *et al.*, 2015; Simpson *et al.*, 2015). High-intensity sounds can inflict physical trauma (McCauley *et al.*, 2003; Dahl *et al.*, 2020; Jenkins *et al.*, 2022) and temporary hearing loss (Smith *et al.*, 2004; Halvorsen *et al.*, 2012; Popper *et al.*, 2007), whereas lower-intensity sounds can mask acoustic signals (Popper and Hawkins, 2019; Putland *et al.*, 2019), alter fish physiology (Debusschere *et al.*, 2016), or modify fish behavior (Slabbekoorn *et al.*, 2010; Purser and Radford, 2011; Simpson *et al.*, 2016a; Pieniazek *et al.*, 2020). However, research gaps remain, with little understanding of how anthropogenic noise affects fish communities and natural fish behavior and how long-term noise affects fish (Hawkins *et al.*, 2015; Nedelec *et al.*, 2016a; Hawkins *et al.*, 2020; Popper *et al.*, 2020).

By conducting a systematic review, the current paper aims to (1) summarize the present literature studying the effects of anthropogenic noise on fish in field settings, (2) interpret and compare the research papers that use differential field methods, and (3) create a guide for researchers who are considering field-based methods and provide a resource that unifies current efforts and highlights innovative techniques.

## II. PAPER COLLECTION METHODS

### A. Literature search

An initial Boolean literature search was conducted using Web of Science (Clarivate Analytics 2022) for studies conducted in the field between the years 2000 and 2022. With the intention of collecting studies that assessed ecologically relevant impacts of anthropogenic noise on fish, papers were filtered to only include those that exposed fish to sound sources in the field. The following was input in the advanced search option: TS=(fish) AND TS=(anthropogenic noise OR noise pollution) AND TS=(field OR wild OR free-swimming), where "TS" referred to "Topic." A secondary search was performed by looking through the cited and "Times Cited" papers of the relevant literature found in the previous search. A final search was conducted to further ensure all studies were acquired falling within the parameters of this review by using slight variations to the search terms described above (e.g., anthropogenic sound, *in situ*, boat noise, etc.). Very few papers published before 2001 met the criteria, and since no appropriate papers were published in 2000, the timespan used for this search was deemed sufficient for detecting all relevant literature and modern techniques. Although we recognize the possibility of missing studies, we are confident our search was highly inclusive with a total of 74 studies for the time span in question.

### B. Data extraction

The information extracted from each paper included the publication year, the data collection method, the metric studied with results, the responses to individual sound sources, and the control used in each study. Nine data collection methods were utilized between the 74 studies: cameras, divers, animal-attached tags, echosounders (sonar), hydrophones, tissue sampling, oxygen consumption, auditory evoked potentials (AEPs), and fishing techniques. The six sound sources investigated in the papers reviewed herein were boat noise, tones, sonar, seismic airguns, pile driving, and divers. Papers using explosives as sound sources were not included due to the multifaceted properties of the stimulus. Papers using more than one form of data collection or sound source were assigned to each appropriate subcategory to account for papers using an integrated approach.

Papers were then categorized based on the metric analyzed (e.g., behavior, physiology, fitness/survival, or an integration of these). Studies were further categorized depending on the results of each study as well as the response to individual sound sources. The resulting effects of noise presented in each study (effects of behavior, physiology, fitness, or habituation) were denoted to studies that found a change in any of the metrics falling under those categories, even if some metrics of the same category did not show effects, but if all metrics showed no effect, they were indicated as such.

The type of sound and the source of presentation in each paper were also recorded, as well as whether that was from the machinery itself or from a speaker. Additionally, the control treatment procedures were noted for each study using a speaker. Since the reporting of particle motion is not always consistent in the literature, this was also documented for each study (Fig. 1). Similarly, papers were assigned as having studied either free-swimming fish or fish in enclosures, with only three studies utilizing both approaches and included in both categories (Hassel *et al.*, 2003; Hassel *et al.*, 2004; McCormick *et al.*, 2018).

## III. SUMMARY OF FIELD TECHNIQUES

There has been an increase in the number of bioacoustics studies investigating the impacts of anthropogenic noise on fish in field settings (Fig. 1), particularly after 2016, as researchers opt to emulate a more natural environmental setting (Hawkins *et al.*, 2015; Popper and Hawkins, 2019). The importance of particle motion measurements has been outlined by Nedelec *et al.* (2016a) and Nedelec *et al.* (2021) and Popper and Hawkins (2018), and almost half the papers in this review (33 of 74) reported the particle motion component of sound in their studies (Fig. 1). In an effort to encourage and continue these trends in field studies, this review summarizes the methods used in previous experiments and offers insights into their advantages and limitations (Table I). Depending on the questions being asked, researchers can utilize enclosures in the field or observe free-swimming fish when investigating the effects of noise.

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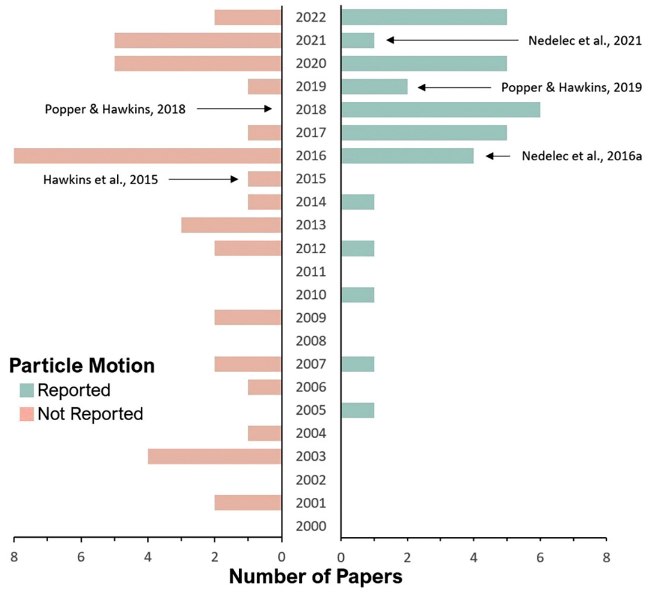

FIG. 1. (Color online) Literature publication trends from 2000 to 2022 of papers directly assessing the role of anthropogenic noise on fish responses in a field setting. Papers are further subdivided by whether or not they reported particle motion. Review papers calling for more field studies (Hawkins *et al.*, 2015; Popper and Hawkins, 2018, 2019) and outlining best practices for measuring particle motion (Nedelec *et al.*, 2016a; Nedelec *et al.*, 2021) were added to show their influence within the field.

Enclosures, in a field setting, can be quite useful for their higher level of experimental control, as studies within this literature review were able to track the entire response of an individual fish (Neo *et al.*, 2016), monitor schooling behaviors (Fewtrell and McCauley, 2012; Ferrari *et al.*, 2018), collect fish for physiological samples post-manipulation (Johansson *et al.*, 2016), and ask specific questions about avoidance using choice chambers that allow the fish to "escape" the noise (Holles *et al.*, 2013). Conversely, enclosures limit fish mobility, which may affect their behaviors and baseline stress levels, and since there are currently no set criteria for optimal cage sizes in field experiments, correlations between studies are difficult to establish (Fewtrell and McCauley, 2012). Enclosure studies, therefore, have limitations, as they could yield their own sound fields depending on their design and restrict free-swimming fish behavior; however, trying to observe free-swimming fish has its own challenges of tracking individuals throughout an experiment and ensuring all fish have the same exposure to a local sound source. Within this review, 33 studies were conducted in enclosed field settings, and 46 were conducted on wild swimming fish [Fig. 2(c)]. Beyond the choice between enclosed and free-swimming fish, there are several methodological approaches used throughout the literature (Table I and Fig. 2).

### A. Camera observations

Advancing technologies have made underwater cameras more accessible than ever (Ulrich and Bonar 2020); thus, cameras were unsurprisingly the most utilized data collection method (29 studies), with most using them to observe behavioral effects [Fig. 2(b)]. Some researchers used cameras to quantify the opercular beat rate (OBR) of fish, but this is categorized as a physiological metric in the current review (Harding *et al.*, 2020; Nedelec *et al.*, 2016b). For free-swimming fish, there were studies that utilized unbaited camera setups, which work well for observing fish with high site fidelity, such as nesting fish (Wardle *et al.*, 2001; Sarà *et al.*, 2007; Picciulin *et al.*, 2010; La Manna *et al.*, 2016; Paxton *et al.*, 2017; McCormick *et al.*, 2018; McCloskey *et al.*, 2020; Nedelec *et al.*, 2022; Fleissner *et al.*, 2022) and can capture the most natural behaviors of fish (La Manna *et al.*, 2016; Paxton *et al.*, 2017; Wardle *et al.*, 2001). Baited underwater video (BUV) systems were used in seven studies (Cole *et al.*, 2007; Mensinger *et al.*, 2016; Roberts *et al.*, 2016; Mensinger *et al.*, 2018; Chapuis *et al.*, 2019; Pieniazek *et al.*, 2020; Fleissner *et al.*, 2022), with BUV systems increasing the number of fish observed and increasing the time fish spend within camera view. Often BUVs are recognized as an effective way of gathering data on natural fish behaviors and community compositions, as they can attract a larger number of fish, but they can also overemphasize the carnivorous fish population (Bernard and Götz, 2012; Whitmarsh *et al.*, 2017; Schramm *et al.*, 2020). The remaining studies (13) used cameras to monitor fish in enclosed setups (Magnhagen *et al.*, 2017; Davidsen *et al.*, 2019; Harding *et al.*, 2020; Woods *et al.*, 2022; Mickle *et al.*, 2022). Cameras are inexpensive, can last longer underwater than a diver (Ghazilou *et al.*, 2019), can have accompanying video analysis programs (Ulrich and Bonar, 2020), and, specifically important for acoustic studies, do not produce sounds that could influence results. However, they can be limited in view as they are mounted in fixed positions and may require extensive time for video analyses.

### B. Diver observations

Traditionally, researchers have manually observed natural fish behaviors and assemblages through an underwater visual census (UVC) conducted by a diver, and in the current review, 11 studies opted for this form of data collection (Cole *et al.*, 2007; Miller and Cripps, 2013; Debusschere *et al.*, 2014; Simpson *et al.*, 2016b; Nedelec *et al.*, 2017a; Nedelec *et al.*, 2017b; Holmes *et al.*, 2017; McCormick *et al.*, 2018; Mills *et al.*, 2020; Brown *et al.*, 2021; Nedelec *et al.*, 2022) [Fig. 2(b)]. While there are more sophisticated methods, UVC is recognized to produce similar fish counts and species compositions to other techniques in fish surveys (Ghazilou *et al.*, 2019; Wetz *et al.*, 2020) and is beneficial for observing cryptic and rare fish species that are hidden within coral (Lowry *et al.*, 2012); however, it does not yield similar results for diver-averse species and may influence fish behavior with the presence of a diver (Assis *et al.*, 2013; Ghazilou *et al.*, 2019). Divers are also limited in the time they can spend underwater as well as how deep they can go when compared to other remote methods of surveying (Wetz *et al.*, 2020).

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TABLE I. Summary table of data collection methods used in various field studies. Confinement level of fish, advantages and disadvantages of each method, type of data obtained, and relevant citations showing each method being used are also included.

| Data collection method | Confinement level | Advantages | Disadvantages | Type of data obtained | Relevant examples |
|---|---|---|---|---|---|
| Camera | Both | Widely accessible, inexpensive, obtains longer video footage than a diver, does not produce sounds that influence results. | Can be limited in view, often requires extensive video analysis. | Behavioral, physiological, fitness | Pieniazek *et al.* (2020);<br>Fleissner *et al.* (2022) |
| Diver | Free-swimming | Produces similar fish counts and species compositions as other techniques, inexpensive, beneficial for observing cryptic and rare fish species. | Low abundances for diver-averse species, diver presence may influence fish behavior. | Behavioral, fitness | Cole *et al.* (2007);<br>Nedelec *et al.* (2016b) |
| Tissue analysis/ sampling | Both | High-resolution data, data collection on various biological levels, easy to integrate with other methods. | Expensive, lethal sampling, invasive. | Physiological, fitness | Amorim *et al.* (2022);<br>McCauley *et al.* (2003) |
| Hydrophone | Both | Minimally invasive, long-term data, observational effects of boat noise. | Unable to know fish distance from the sound source or how many are calling, only works on actively calling species. | Behavioral | Mackiewicz *et al.* (2021);<br>Higgs and Beach (2021) |
| Echosounder/ sonar | Free-swimming | Allows for the study of pelagic fish behavior, schooling, water column changes. | Difficulty identifying species, fish must be larger than 10 cm, potential interference with marine mammal behavior. | Behavioral | Peña *et al.* (2013);<br>Hawkins *et al.* (2014) |
| Tag | Free-swimming | Tracks fish movement over large areas, monitors detailed and individualized responses, assesses diurnal responses and immediate physiological responses, long-term data. | Expensive, can require surgery for implantation (invasive), can only be used on larger fish. | Behavioral, physiological | Ivanova *et al.* (2020);<br>Van der Knaap *et al.* (2021) |
| Oxygen level | Enclosed | Allows for a better understanding of overall stress. | Potential for confounding factors and sound distortion. | Physiological | Harding *et al.* (2018);<br>Debusschere *et al.* (2016) |
| Catch rates | Free-swimming | Inexpensive, accessible, community and/or commercial involvement, long-term data. | Difficult to be species-selective, often size-selective, possibility of bycatch. | Behavioral | Løkkeborg *et al.* (2012);<br>Hassel *et al.* (2003);<br>Hassel *et al.* (2004) |
| AEP | Enclosed | High-resolution data, detects hearing threshold shifts. | Expensive, physically invasive procedure, variable between labs. | Physiological | Halvorsen *et al.* (2012);<br>Popper *et al.* (2007) |

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## C. Tissue sampling

There were 11 studies that collected fish for tissue sampling after being exposed to sound in the field (McCauley *et al.*, 2003; Popper *et al.*, 2007; Kane *et al.*, 2010; Debusschere *et al.*, 2016; Johansson *et al.*, 2016; Nedelec *et al.*, 2016b; Popper *et al.*, 2016; Staaterman *et al.*, 2020; Mills *et al.*, 2020; Amorim *et al.*, 2022; Faria *et al.*, 2022) [Fig. 2(b)]. Tissue samples can be used to assess physiological noise stress using primary stress indicators that involve the release of catecholamines (e.g., epinephrine and norepinephrine) and corticosteroids (e.g., cortisol) into the blood and surrounding tissues (Barton, 2002; Wendelaar Bonga, 1997). Cortisol has become a popular measure of noise-induced stress in fish as it is easily accessible and can be measured at both baseline and stress-induced levels, a beneficial trait for accurate, species-specific studies (Friebertshauser *et al.*, 2020; Guh *et al.*, 2021; Lara and Vasconcelos, 2021). There are additional, novel, hormone measures (e.g., androgens) being used alongside cortisol in recent studies that have been shown to be affected by sound (Mills *et al.*, 2020). Seven studies looked at hormonal changes of noise exposed fish in the field (Johansson *et al.*, 2016; Debusschere *et al.*, 2016; Nedelec *et al.*, 2016b; Staaterman *et al.*, 2020; Mills *et al.*, 2020; Amorim *et al.*, 2022; Faria *et al.*, 2022). In addition to hormonal changes seen in response to noise, fish have several anatomical structures that can be affected by noise exposure, including their inner ear organs and swim bladders (Kane *et al.*, 2010; Kunc *et al.*, 2016; Popper *et al.*, 2016). Damage caused by sound exposure is often due to high intensities near the source [see Fig. 2 in Slabbekoorn (2019)] and can be quantified through dissections of hearing structures to assess damage (e.g., Popper *et al.*, 2007; Kane *et al.*, 2010). There were four field studies included in this review that quantified the effects of sound on anatomical structures (McCauley *et al.*, 2003; Popper *et al.*, 2007; Kane *et al.*, 2010; Popper *et al.*,

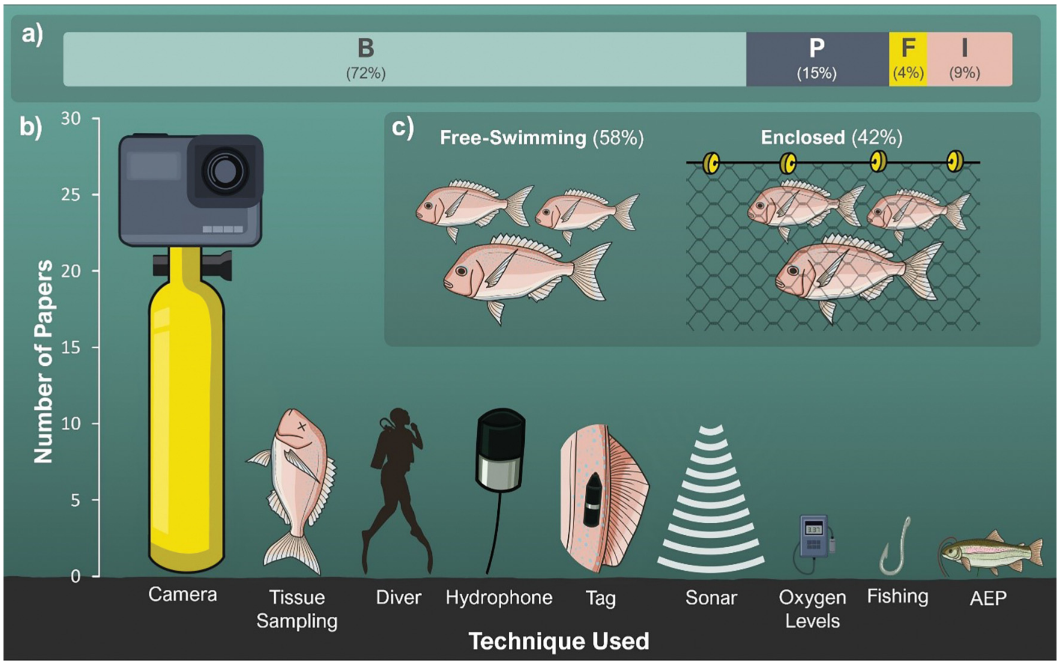

FIG. 2. (Color online) (a) Proportional representation of the metrics studied in publications assessing the impact of anthropogenic noise on fish responses (B, behavioral; P, physiological; F, fitness; I, integrated). (b) Literature publication trends of techniques used to collect data in field studies assessing the impact of anthropogenic noises on fish. (c) Proportional representation of papers assessing fish responses in a free-swimming setting vs in an enclosed setting.

2016). Understanding the physiological effects of sound through tissue sampling is a common, albeit more invasive and logistically difficult, way to measure fish stress in the field as fish must often be contained to retrieve tissue samples following noise exposure; however, visualizing damage can be beneficial in confirming negative effects.

## D. Hydrophones

A total of 11 papers in this review used hydrophones to monitor the responses of fish to anthropogenic noise (Luczkovich *et al.*, 2016; Stanley *et al.*, 2017; Higgs and Humphrey, 2020; Pyć *et al.*, 2021; Mackiewicz *et al.*, 2021; Brown *et al.*, 2021; Higgs and Beach, 2021; Pine *et al.*, 2021; Amorim *et al.*, 2022; Siddagangaiah *et al.*, 2022) [Fig. 2(b)]. Hydrophones or passive recorders are useful, minimally invasive tools that can be used to record and analyze sound in aquatic environments (Higgs and Humphrey, 2020; Ross *et al.*, 2023). Hydrophones can be especially useful in logistically difficult environments (i.e., deep water or turbid environments) and can provide continuous monitoring over long periods of time (Pyć *et al.*, 2021) both during the day and at night, which is not an easy or common task. By recording sounds produced in aquatic environments, researchers can retrieve high-resolution information about environmental conditions and species diversity and abundance and potentially identify cryptic or endangered species environments (Desjonquères *et al.*, 2020). Passive observation of the effects of noise on fish remains an enticing cost-effective and minimally invasive technique for monitoring wild, free-swimming fishes and has the potential to answer questions about presence, vocal behaviors, masking, communication space estimations, and environmental conditions (Stanley *et al.*, 2017; Putland *et al.*, 2018; Ivanova *et al.*, 2020; Pine *et al.*, 2021; Pyć *et al.*, 2021). However, using hydrophones can have certain drawbacks, such as only allowing for work on actively calling species and not being able to definitively state how far fish are from the sound source and how many fish are calling (Linke *et al.*, 2018; Higgs and Beach, 2021).

## E. Echosounder/sonar

Fish-finding sonar systems (echosounders) were used in ten papers (Slotte *et al.*, 2004; Hassel *et al.*, 2003; Handegard *et al.*, 2003; Hassel *et al.*, 2004; Jorgenson and Gyselman, 2009; Doksaeter *et al.*, 2009; Cott *et al.*, 2012; Peña *et al.*, 2013; Hawkins *et al.*, 2014; Kok *et al.*, 2021) and offer a unique opportunity to study pelagic species and their schooling behaviors in response to anthropogenic noise [Fig. 2(b)]. Echo sounder and sonar systems produce high frequency sound pulses, which are outside the range of fish hearing for most species (18–38 kHz and >200 kHz, respectively) and reflect off fish to determine their approximate locations between the sounder and the seafloor (Handegard *et al.*, 2003; Slotte *et al.*, 2004; Hawkins *et al.*, 2014). However, sonar alone is limited to detecting fish larger than roughly 10 cm and has difficulty distinguishing fish species (Egg *et al.*, 2018). Sonar also has the potential to interfere with the behavior of marine mammals, causing negative health and fitness consequences, and care should be taken when using it in shared environments [as reviewed in Ketten (2012)].

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### F. Animal-attached tags

Aquatic animal-attached tags can also benefit the field of underwater bioacoustics, as they can provide physiological information (e.g., heart rate, body temperature, etc.) through biologgers, movement data (e.g., tailbeats, acceleration, migrations, etc.), accelerometers, acoustic receivers, environmental data (e.g., water temperature, depth, soundscapes, etc.), sensors, and hydrophones (Johnson and Tyack, 2003; Hussey *et al.*, 2015). There were ten studies that collected data using animal-attached tags, with all but one (Davidsen *et al.*, 2019) utilizing acoustic transmitters to assess behavior and movements (Wardle *et al.*, 2001; Iafrate *et al.*, 2016; Neo *et al.*, 2016; Neo *et al.*, 2018; Bruce *et al.*, 2018; Davidsen *et al.*, 2019; Ivanova *et al.*, 2020; Hubert *et al.*, 2020a; Hubert *et al.*, 2020b; van der Knaap *et al.*, 2021) and two that also used accelerometers (Hubert *et al.*, 2020a; Hubert *et al.*, 2020b). Tags also offer solutions to avoid the constraints that cameras put on field enclosure sizes by tracking fish movements over larger areas, which can increase the behavioral efficacy of field enclosures while still providing an element of experimental control (Neo *et al.*, 2018). Animal-attached tags monitor more detailed and individualized responses of fish to sound and offer a unique advantage when assessing the diurnal effects of noise on swim patterns (Neo *et al.*, 2018; van der Knaap *et al.*, 2021) and the immediate physiological responses of fish to sound (Davidsen *et al.*, 2019). Tags can also record the behaviors and movements of free-swimming fish over longer periods of time than cameras (Iafrate *et al.*, 2016), but there is still the problem of ensuring all fish receive the same treatments and intensities of anthropogenic sounds. Additionally, animal-attached tags can only be used on larger fish, are typically more expensive than other techniques mentioned, and are more invasive than other techniques, since they often require surgery to embed the tags in fish and, therefore, create more risk to the animal (Hussey *et al.*, 2015; Harcourt *et al.*, 2019).

### G. Oxygen consumption

Within this review, four papers used oxygen consumption to measure noise stress (Simpson *et al.*, 2015; Simpson *et al.*, 2016b; Debusschere *et al.*, 2016; Harding *et al.*, 2018) [Fig. 2(b)]. Oxygen consumption is a long-standing measure of energy use and is considered a secondary physiological response that is an immediate result of the primary stress responses (Barton, 2002; Wendelaar Bonga, 1997). Noise pollution can trigger the stress response axis, causing a cascade of physiological changes that researchers are able to directly quantify as a measure of stress or as a secondary proxy allowing for a better understanding of stress overall (Debusschere *et al.*, 2016). Oxygen consumption rates are quantified by measuring the resulting oxygen levels in a closed container, which can be difficult to achieve in the field (Chabot *et al.*, 2016). In all papers included in this review, fish were sealed in containers, suspended in the natural environment, and exposed to various types of noise. While this maintains some semblance to the natural environment, holding fish in small plastic containers can result in confounding factors contributing to changes in oxygen consumption, such as added confinement stress, and the effects seen can be difficult to compare across studies (Chabot *et al.*, 2016). Additionally, although the containers are said to be acoustically transparent, it is possible that the sound is somewhat distorted over the course of the experiments, so until rigorous testing can confirm, this method should be used with caution.

### H. Catch rates

Catch rates of fish were used in four studies within the current review [Fig. 2(b)] and can provide a more commercially relevant way of assessing the behavioral effects of anthropogenic noise (Hassel *et al.*, 2003; Hassel *et al.*, 2004; Løkkeborg *et al.*, 2012; Simpson *et al.*, 2016a). Fishing is a technique commonly used for population or stock assessments and can utilize a variety of different gear types, such as gillnets, long lines, and trawling, or in some cases using modified cages to trap fish following experiments (Engås *et al.*, 1996; Hassel *et al.*, 2003). Catch rates are a very straightforward way to assess populations as well as mortality, but overall, this technique is often biased toward fish of similar sizes (depending on gear types) and is not species-specific, which can lead to underrepresentation of fish populations and unnecessary bycatch.

### I. AEPs

AEPs, previously called auditory brainstem responses (ABRs), are electrophysical measures of sound detection in the ear and brain (Popper and Hawkins, 2021). The use of AEPs has been extensively reviewed by Ladich and Fay (2013) and has become a popular way to measure sound response thresholds and threshold shifts due to noise exposure in fish under varying circumstances. AEP procedures require the insertion of several electrodes into the tissue surrounding these auditory structures and are classically conducted in tanks (Ladich and Fay 2013), so there was hesitation to include such studies in this review. However, AEPs have previously been successful when performed in the field (Chapman, 1973; Chapman and Hawkins, 1973; Chapman and Johnstone, 1974; Hawkins *et al.*, 2014). There were three studies that were included in this review; however, it is important to note that the fish were exposed to noise in the field and then transported to a laboratory setting for AEP assessment (Popper *et al.*, 2005; Popper *et al.*, 2007; Halvorsen *et al.*, 2012) [Fig. 2(b)]. Understandably, AEP studies are logistically difficult to conduct in a field setting, as the equipment required to determine AEPs is expensive; however, it is possible, as shown by the studies included here. Studies using AEPs can also be highly variable between fish of the same species under differing conditions (Ladich and Fay, 2013), so, as with behavioral studies, results must be interpreted and compared with caution. Finally, AEPs, while “minimally invasive” from a

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physiological perspective, do have an increased risk of complications that often accompany any procedure where fish must be anesthetized.

## IV. INTERPRETATION OF RESEARCH METRICS AND SOUND SOURCES

The findings from the 74 papers in this review show strong evidence that a variety of anthropogenic sound sources in aquatic environments affect fish in a multitude of ways. Most field studies investigating the impacts of anthropogenic sounds on fish thus far have focused on using behavioral metrics to do so (53 of 74), with fewer studying metrics of physiology (11 of 74) and integrated approaches (7 of 74) and even fewer tackling fitness/survival (3 of 74) [Fig. 2(a)]. From these data, there were 48 papers that reported behavioral effects, 13 that reported physiological effects, five that reported effects on survival, eight that reported evidence of habituation, and 13 that showed no effects of noise on fish (Fig. 3). However, the results found throughout the papers reviewed vary in terms of impact, methodologies, sound intensities, species, etc.; therefore, the results presented below for each sound source are based only on the number of papers with similar overall findings.

### A. Control sounds

When presenting an experimental sound using a speaker, it is important to have appropriate controls. Previous papers have presented either ambient sound or no sound through a speaker that is still present in the experimental setup or removed from the setup entirely. Of the 28 studies that used a speaker for sound presentation, 15 studies presented ambient sound as a control, eight left the speaker in place but presented no sound through it (either with the speaker still connected to the amplifier or the speaker completely disconnected), two removed the speaker from the experimental area completely, and two presented no sound but did not specify the conditions. Playing ambient sound back through a speaker is thought by some to be a more rigorous control than playing no sound at all, although if the ambient sound is played at background sound levels, it may be thought of as essentially silent in the view of the fish. It is desirable to leave a speaker in place as a control in case it serves as a visual cue, although no one to our knowledge has rigorously tested the effects of these different control settings, and until this is done, it is not possible to judge the suitability of one control type over another [Fig. 4(b)].

#### *1. Boat noise*

Most field studies to date have assessed the effects of vessel noise on wild fish (40 of 74), which is appropriate considering boats are the most common source of anthropogenic sound in many aquatic soundscapes (Simpson *et al.*, 2016a; Simpson *et al.*, 2016b; Holmes *et al.*, 2017; Nedelec *et al.*, 2017a; Nedelec *et al.*, 2017b; Slabbekoorn *et al.*, 2010). There were 18 studies that assessed the effects of boat noise on fish using playbacks relayed through a speaker, while 22 studies opted for a real outboard motor. Furthermore, 26 of those 38 total studies assessed the effects of boat passes on fish, with seven of those using speakers to produce the sound as opposed to motors, while 14 studies used stationary vessel sounds, 11 of which used speakers, with the remainder using actual motors [Fig. 4(a)].

The sound produced from boats has been found to elicit behavioral changes in 29 studies, physiological changes in seven, and changes in fitness/survival metrics in five studies. Alternatively, six studies found that fish habituated to boat noise over time, while two found no effect on boat noise (Fig. 3). Behaviorally, vessel noise led to escape responses in, or the dispersion of, many species, including juvenile common damselfish (*Pomacentrus amboinensis*; Holmes *et al.*, 2017), southern stingrays (*Hypanus americanus*; Mickle *et al.*, 2022), and Arctic cod (B*oreogadus saida*; Ivanova *et al.*, 2020) and increased hiding behavior in threespot dascyllus (*Dascyllus trimaculatus*; Nedelec *et al.*, 2016b) and orange-fin anemonefish (Mills *et al.*, 2020). It has also been shown to decrease foraging behaviors in several shark species (order: Carcharhiniformes; Chapuis *et al.*, 2019) and

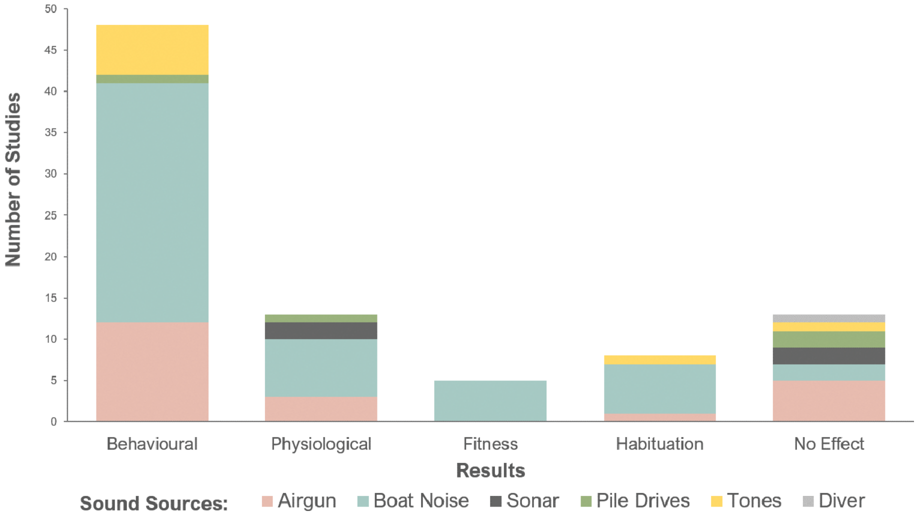

FIG. 3. (Color online) The number of studies reporting effects on behavior, physiology, fitness and survival, and habituation, as well as no effects, for each sound source.

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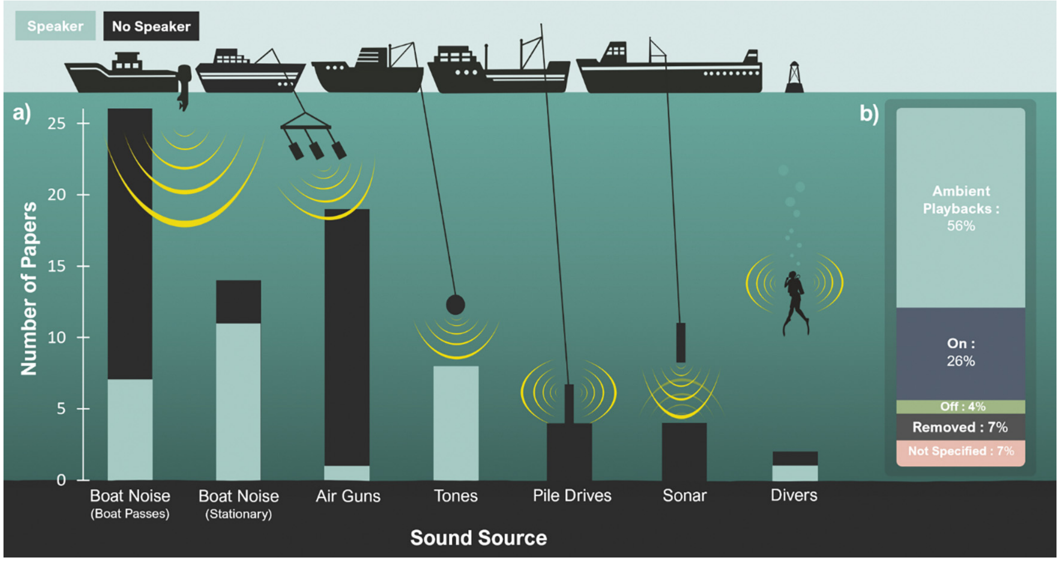

FIG. 4. (Color online) (a) Literature publication trends of sound sources used in field studies directly assessing the impact of anthropogenic sounds on fish responses (from papers published between 2000 and 2022). Findings are further divided into the number of studies that used speaker playbacks or the actual sound sources during exposures. (b) Proportional representation of the types of controls used for studies that opted for speaker sound sources.

freshwater fish (Pieniazek *et al.*, 2020) and communication ranges for Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*; Stanley *et al.*, 2017). Additionally, boat noise can lead to physiological effects, as seen with elevated oxygen consumption rates in Lake Malawi cichlids (*Cynotilapia zebroides*; Harding *et al.*, 2018) and Ambon damselfish (*Pomacentrus amboinensis*; Simpson *et al.*, 2016b), reduced heart rate in Atlantic cod (Davidsen *et al.*, 2019), and increased cortisol levels in Eurasian perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*; Johansson *et al.*, 2016). Boat noise also has the ability to affect the fitness and survival of free-swimming fish, for it reduced parental care and larval survival in wild spiny chromis (*Acanthochromis polyacanthus*; Nedelec *et al.*, 2017b), plainfin midshipman (*Porichthys notatus*; Woods *et al.*, 2022), and Lusitanian toadfish (*Halobatrachus didactylus*; Amorim *et al.*, 2022; Faria *et al.*, 2022) and disrupted orientation and settlement of coral reef fish (Holles *et al.*, 2013; Simpson *et al.*, 2016a).

There seems to be a trend supporting previous laboratory findings with short-term boat noise exposure changing fish behavior and survival; however, literature also suggests wild fish may be more adept at enduring long-term vessel noise than initially thought (Nedelec *et al.*, 2016b; Holmes *et al.*, 2017; Harding *et al.*, 2018). Fish regularly exposed to fishing pressures appeared to be more reactive to boat noise than those residing in protected areas; for example, Mensinger *et al.* (2018) found that protected Australasian snapper (*Pagrus auratus*) did not react behaviorally to boats passing, whereas those in open fishing regions dispersed more and decreased foraging efforts. Wild fish have also shown an increased tolerance to vessel noise after long-term exposure, with both experimental boat sound playbacks (Nedelec *et al.*, 2016b; Johansson *et al.*, 2016; Holmes *et al.*, 2017) and naturally occurring boat sounds in high-traffic areas (Harding *et al.*, 2018) leading to apparent habituation. Additionally, McCormick *et al.* (2018) found that juvenile damselfish (*Pomacentrus wardi*) responded to two-stroke outboard boat motors, but not to four-stroke outboard boat motors. Therefore, engine type may play a key role in determining the responses of wild fish to boat noise; thus, more research is necessary in determining how other engine types affect such responses.

### B. Seismic airguns

There were 19 studies exploring the impacts of seismic airgun strikes [Fig. 4(a)], with 12 finding changes in fish behavior, three finding physiology effects (McCauley *et al.*, 2003; Popper *et al.*, 2005; Davidsen *et al.*, 2019), one reporting habituation effects (Davidsen *et al.*, 2019), and five reporting no effect of seismic noise on fish (Jorgenson and Gyselman, 2009; Miller and Cripps, 2013; Peña *et al.*, 2013: Popper *et al.*, 2016; Bruce *et al.*, 2018) (Fig. 3). Therefore, a wide range of effects have been observed on fish in response to seismic noise, but with only three studies collecting physiological metrics, such as hair cell damage (McCauley *et al.*, 2003), reduced heart rates (Davidsen *et al.*, 2019), and hearing threshold shifts (Popper *et al.*, 2005), and none assessing fitness or survival effects, inferences can only be made from the behavioral data (Fig. 3). There were several studies identifying changes in swimming patterns (Slotte *et al.*, 2004; Fewtrell and McCauley, 2012; Løkkeborg *et al.*, 2012; van der Knaap *et al.*, 2021) and foraging (Løkkeborg *et al.*, 2012), with one even finding diurnal variation (van der Knaap *et al.*, 2021). Fish also showed diminished responses after repeated exposures to airguns, which further suggests that fish may be able to habituate to anthropogenic noise (Davidsen *et al.*, 2019), but further

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investigation is necessary to determine whether it is truly increased tolerance or decreased hearing sensitivity. Løkkeborg *et al.* (2012) reported a doubling of catch rates in gill nets of redfish (*Sebastes norvegicus*) and Greenland halibut (*Reinhardtius hippoglossoides*) during seismic testing, but lower catch rates on long lines for Greenland halibut and haddock (*Melanogrammus aeglefinus*), suggesting fish increased swimming activity and decreased foraging behaviors in response to seismic airguns.

### C. Tones

Artificially derived sounds were used in eight papers and can allow for a deeper understanding of fish hearing through field-based behavioral audiograms (Hawkins *et al.*, 2014; Mickle *et al.*, 2020) and offer the opportunity to control the sound structure and variability during noise exposure experiments (Neo *et al.*, 2016; Hubert *et al.*, 2020b) [Fig. 4(a)]. The studies using tones focused on behavioral effects (Hawkins *et al.*, 2014; Mickle *et al.*, 2020; Brown *et al.*, 2021), physiological effects (Halvorsen *et al.*, 2012), habituation (Neo *et al.*, 2018), and effects that were dependent on data metrics (Fig. 3; Hubert *et al.*, 2020b). Two of the behavioral studies used tones to establish a threshold of responsiveness with free-swimming sprat (*Sprattus sprattus*) and mackerel (*Scomber scombrus*; Hawkins *et al.*, 2014) and enclosed southern stingrays (*Hypanus americanus*; Mickle *et al.*, 2020), which could assist in creating guidelines for policymakers to guide implementation. Neo *et al.* (2018) also highlighted the possibility that fish may have stronger responses to tones at night when comparing swim patterns of fish over two days, which suggests further investigation is necessary, as this could be useful information when developing protection plans if fish are more affected at night.

### D. Pile driving

The effect of pile driving was examined in five papers, which can provide valuable insight about the effects of increasing levels of construction in aquatic environments (Debusschere *et al.*, 2014; Debusschere *et al.*, 2016; Iafrate *et al.*, 2016; Kok *et al.*, 2021; Siddagangaiah *et al.*, 2022) [Fig. 4(a)]. Fish showed mixed responses when exposed to pile driving, which could be due, at least in part, to both a difference in hearing abilities across species and a difference in scope between studies (e.g. behavioral data collection vs physiological data collection) (Fig. 3). Debusschere *et al.* (2014) conducted an *in situ* study to determine the risk of mortality of juvenile European sea bass (*Dicentrarchus labrax*) at offshore windfarm construction sites and found that there was no difference in immediate or delayed mortality between exposed and non-exposed fish. In a follow-up study, Debusschere *et al.* (2016) exposed juvenile sea bass to pile drive sounds to determine whether there were physiological indicators of primary (whole-body cortisol) and secondary (oxygen consumption and whole-body lactate) stress. Fish exposed to the noise showed a reduced oxygen consumption rate and a decrease in whole-body lactate levels (Debusschere *et al.*, 2016). Both sheepshead (*Archosargus probatocephalus*) and gray snapper (*Lutjanus griseus*) exposed to pile driving showed that only gray snapper showed any behavioral changes in movement patterns, suggesting that the responses to noise may be species-specific (Iafrate *et al.*, 2016). With the recent increase in construction of offshore wind farms, pile driving has become a more prevalent source of noise (Kok *et al.*, 2021), creating an opportunity for researchers to explore the effects of green energy construction on surrounding ecosystems. Recent efforts to understand impacts of pile driving at construction sites have shown that pelagic fish may change their swimming behavior in the presence of pile driving at windfarm sites (Kok *et al.*, 2021) as well as their vocalizations depending on the presence of both construction (pile driving) and operation of offshore wind farms (Siddagangaiah *et al.*, 2022). However, both studies highlight the need for additional research to be conducted in these areas of study, as it will become a more pressing problem with the continued development of offshore windfarms.

### E. Sonar

There have been four papers that report on the effects of sonar signals of different frequency ranges and exposure levels on fish responses in a field setting (Doksaeter *et al.*, 2009; Halvorsen *et al.*, 2012; Kane *et al.*, 2010; Popper *et al.*, 2007) [Fig. 4(a)]. The reported responses to sonar were physiological in nature (Halvorsen *et al.*, 2012; Popper *et al.*, 2007); however, two of the four studies included in this review reported no effects when assessing behavior (Doksaeter *et al.*, 2009) and anatomical structures (Kane *et al.*, 2010) (Fig. 3). While more work needs to be done, the available evidence suggests that sonar sources are not likely to significantly affect fish, especially at realistic source levels and if fish are not exposed directly at the source level.

### F. Diver sound

Only one paper explored the effects of noise from diver breathing apparatus (Cole *et al.*, 2007), but this source of anthropogenic noise was included since using divers to collect data is common. Cole *et al.* (2007) conducted fish counts with exposure to open-circuit scuba and rebreather noise with and without a diver present and observed similar results between all treatments, suggesting little effect of diver sounds. While follow-up experiments would be beneficial in confirming such findings, as it stands, diver sounds do not appear to affect fish behavior or presence, although they are within the realm of their hearing (Radford *et al.*, 2005).

## V. FUTURE DIRECTIONS AND EMERGING APPROACHES

While the current literature has used an impressive arsenal of effective methods of collecting data, there are still some less-used techniques that pose intriguing ways of understanding the effects of anthropogenic noise on fish.

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Drones and remote-operated vehicles (ROVs) present a compelling method for observing wild fishes, from the perspective of the fish, while also having the ability to access environments and conduct experiments that are more logistically difficult, which could expand our realm of reasonable research questions. Diver observations in shallow water environments (divers holding GoPros) and ROVs yielded nearly identical results when comparing quantifications of abundance, diversity, and behavior, with ROVs in some cases providing more robust data (Raoult *et al.*, 2020). Additionally, it has been suggested that ROVs used in offshore oil and gas industries could be retrofitted with scientific instruments to collect environmental data and observe a variety of marine species (McLean *et al.*, 2020). While ROVs seem to have high potential for monitoring fish, these vehicles produce their own sound and should be used with caution, and appropriate measures should be taken to ensure they do not influence or alter fish responses (Wetz *et al.*, 2020).

Researchers studying the effects of anthropogenic noise on marine mammals have taken to using novel archival digital acoustic recording tags (DTAGs) (Holt *et al.*, 2017; Erbe *et al.*, 2019; Parks *et al.*, 2019: Christiansen *et al.*, 2020), which contain integrated hydrophones or sonar within the tag in addition to accelerometers, magnetometers, and depth and temperature sensors (Johnson and Tyack, 2003). DTAGs have been used to identify vessel speed as the main predictor of noise levels surrounding killer whales (*Orcinus orca*: Houghton *et al.*, 2015) and to establish the parallel relationship between cetacean responses to soniferous predators and anthropogenic noise (Miller *et al.*, 2022). Since their introduction, DTAGs have mainly been used on marine mammals, but a recent study demonstrated their successful use on Greenland sharks (*Somniosus microcephalus*; Ste-Marie *et al.*, 2022). Therefore, these tags have the potential to monitor the direct soundscapes perceived by fish and to characterize behavioral responses to naturally occurring anthropogenic sounds; however, studies would be limited to the movements of large free-ranging fish or elasmobranch species.

A special mention should be made of novel studies examining the effects of noise on gene transcription in fish. The measurement of transcriptional changes as an indicator of stress has been used in previous studies to estimate the effects of other environmental stressors (Akbarzadeh *et al.*, 2018; Bernos *et al.*, 2020; Connon *et al.*, 2018; Logan and Buckley, 2015; Prunet *et al.*, 2008), but this approach has not yet realized its full potential in examinations of noise stress. In general, when fish are exposed to a stressor, it causes shifts in metabolic efforts (reallocating resources and mobilizing fat stores), reduces growth, and suppresses both the immune and reproductive systems as they are energetically costly (Balasch and Tort, 2019; Pankhurst, 2011; Wendelaar Bonga, 1997). At the molecular level, this translates to an up- or down-regulation of genes involved in pathways that mediate the changes in energetically costly systems (Aluru and Vijayan, 2009). In the first study on fish to explore the effects of sound at a transcriptional level, vessel noise was played to gilthead sea bream (*Sparus aurata*) in a captive setting, and several biological metrics, including the expression of a well-conserved family of heat shock protein (Hsp70), were used to determine stress levels from blood plasma samples (Celi *et al.*, 2016). Since then, several other laboratory studies have used gene expression to measure stress responses of fish to noise. Female African cichlid fish (*Astatotilapia burtoni*), a mouthbrooding species, exposed to a range of tones (100–2000 Hz) were found to have almost 1200 genes differentially expressed in the hypothalamus compared to the control fish (Butler and Maruska, 2021), suggesting significant implications for their reproduction and fitness. Furthermore, Lithuanian toadfish (*Halobatrachus didactylus*) larvae, when exposed to boat noise, show significant increases in superoxide dismutase (SOD), a potential for minor DNA damage, and unfavorable effects on growth, implying increased amounts of harmful molecular and physiological stress (Faria *et al.*, 2022). As this is a newer metric for assessing acoustic stress, all studies to date using gene transcription as a measure of stress have been conducted in a lab setting. However, this is not to say that genetic analysis cannot be conducted in the field, using wild fish (Beach, 2022).

## VI. KEY POINTS AND RECOMMENDATIONS

Fish bioacoustic researchers seem to collectively agree that more field testing is necessary to realistically assess the effects of anthropogenic noise on fish, as the number of papers published has considerably increased within the last decade (Neo *et al.*, 2018; Mensinger *et al.*, 2018; Davidsen *et al.*, 2019; Mills *et al.*, 2020; Staaterman *et al.*, 2020) (Fig. 1). Studies have either taken to using enclosures for more experimental control or assessed free-ranging fish to further increase the ecological validity of their results. Boat noise was the most common sound source studied (Fig. 4), and there is now field evidence to support that such noise can negatively impact wild fish that encounter it. However, the results of field studies indicate there are more complex responses to noise than the overwhelmingly negative consequences found in laboratory studies (Fig. 4). Noise impacts may depend on the location or habitat, species-specific responses, sex, life stage, fishing pressures, noise tolerance, sound source level, and hearing thresholds of fish (Fewtrell and McCauley, 2012; Mensinger *et al.*, 2018; Davidsen *et al.*, 2019; Mickle *et al.*, 2020). Therefore, while field studies are important for understanding the effects of anthropogenic noise on fish, care must be taken when designing future experiments to ensure that the data allow for appropriate interpretations of research questions.

Here, we will highlight a few specific recommendations based on information collected from the studies in the current review.

(1) Continued effort must be made to collect and characterize the particle motion as well as sound pressure levels and propagation distances (Hawkins *et al.*, 2020), so

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that further research might discover productive uses for particle motion measurements. While this remains a challenge due to costly and complex equipment, there have been encouraging improvements in instrument availability and standardization of measurement that will hopefully lead to better sound characterization in future studies (Nedelec *et al.*, 2016a; Nedelec *et al.*, 2021; Wilson *et al.*, 2023).

(2) Careful comparisons should be made between field and lab studies on the same species. While lab studies have come under criticism recently (Popper and Hawkins, 2021), they can still provide value in many instances and are more easily controlled than field studies (e.g., Simpson *et al.*, 2016b, Pieniazek *et al.*, 2020). So although we do recognize the increased effort put into field-based measurements, it would be a mistake to completely disregard the lab approach.

(3) Field behavioral response thresholds, like those demonstrated by Mickle *et al.* (2020) and Hawkins *et al.* (2014), should be expanded on, as they give a more realistic estimation of what sounds and sound levels are relevant to the species of interest. Response thresholds are often much higher than hearing thresholds (Ladich and Fay, 2013; Hawkins *et al.*, 2020), and therefore, field characterization of response thresholds would benefit our understanding of fish hearing and noise pollution impact.

(4) Increased efforts should be taken to avoid repetition in assessing the effects of noise on the same species. While it is not possible to test them all, there is still a great deal of variation in the responses across fish species and habitats in the literature, making it difficult to identify trends (Fewtrell and McCauley, 2012; Halvorsen *et al.*, 2012; Mensinger *et al.*, 2018; Davidsen *et al.*, 2019). Multiple species experiments could help increase efficiency and achieve an appropriate level of comparison within the field to draw conclusions about species-specific hearing and responses.

(5) Most studies thus far have assessed the effects of boat noise on wild fish, and while that is proportionally appropriate because it is the most common form of underwater noise, there is still a need for understanding the effects of resource exploration activities and construction as interest in oil and offshore windfarms continues to increase (Carroll *et al.*, 2017; Popper *et al.*, 2022).

(6) Further research is needed to understand the long-term effects of noise on wild fish (Johansson *et al.*, 2016; Holmes *et al.*, 2017; Harding *et al.*, 2018) and whether auditory or physical damage occurs. While the evidence for habituation is encouraging, only eight papers of 74 measured and reported such results, and none of them accounted for the possibility that diminished responses could be due to hair cell damage and hearing threshold shifts (Popper *et al.*, 2005; Popper *et al.*, 2007; Halvorsen *et al.*, 2012). Therefore, the degree of physical damage noise can cause to a fish or the levels at which they can habituate, or at least tolerate, noise remains a serious gap in the field and is critically important when setting exposure guidelines. If fish can adapt to and ignore noise sources, then the need for mitigation may be reduced, but until these effects are much better understood, it is hard to accurately represent the true impacts of these noise sources.

(7) Increased efforts should be put into quantifying physiological and fitness effects of noise on fish. While showing a fish has a short-term response to a noise input is important, it is only by quantifying long-term effects and true fitness effects (e.g., reduced spawning, stunted growth) that we will be able to understand when noise is a significant problem for fishes and when it is a temporary irritant (Hawkins and Popper, 2017). Future studies could also explore both stress-related and other biological process genes to narrow down a suite of genes suitable for examining noise stress, as this technique provides useful insight to changes on a molecular level.

(8) Integrated studies could be a valuable resource in producing high-resolution data of anthropogenic noise impacts on wild fish (Mickle and Higgs, 2018; Przeslawski *et al.*, 2018). There are a host of field-based data collection methods, and while each method has its own limitations, a combination of techniques could provide a more comprehensive and accurate representation of natural fish responses to noise and lead to more robust interpretations (Lowry *et al.*, 2012; Schramm *et al.*, 2020; Wetz *et al.*, 2020).

Existing underwater acoustic field studies have provided valuable evidence for methodologies that function well and have furthered our understanding of how noise can affect fishes; however, more investigation is required to appropriately use such findings for real-world applications. Furthermore, there appears to be a great deal of variation in the responses between species (Fewtrell and McCauley, 2012; Mensinger *et al.*, 2018; Davidsen *et al.*, 2019), and understanding where such differences exist is imperative for future mitigation. Reviews, such as Hawkins *et al.* (2015), Hawkins *et al.* (2020), and Popper *et al.* (2020), already describe in detail some of the areas in which research is lacking in the present field, and hopefully the current review can help focus future efforts, inform researchers of past successes and downfalls, and provide insights into how field studies can be carried out.

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